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FOR (d, α) REACTION ON SCANDIUM 45

by Joseph R. Priest and John S. Vincent

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SUMMARY

The differential cross sections corresponding to the production of the ground and first five excited states of calcium 43 in the $\text{Sc}^{45}(\text{d}, \alpha)\text{Ca}^{43}$ reaction were measured for a deuteron energy of 20.9 MeV (33.5×10^{-13} J). The angular distribution for the ground-state transition extends from 15° to 170° ; the remaining angular distributions range from 15° to 100° . The differential cross sections for the ground-state transitions are, in general, more than 10 times larger than those for the transitions to excited states; this is interpreted to be a consequence of the large overlap of the ground-state configurations of scandium 45 and calcium 43. The differential cross sections for production of two core-excited states of Ca^{43} are small (1 to $10 \mu\text{b/sr}$; 10^{-34} to $10^{-33} \text{ m}^2/\text{sr}$) but not negligible and are comparable to those of the other excited states investigated. The interpretation of the reaction mechanism for these transitions poses an interesting theoretical problem.

INTRODUCTION

In many nuclei there exist low-lying energy states which, within the shell-model formalism, require an excited nuclear core for their description. A (d, α) reaction leading to these states by a direct interaction mechanism should be a second-order process. The second excited state of oxygen 17 is such a state.

In a study of $\text{F}^{19}(\text{d}, \alpha)\text{O}^{17}$ reactions (ref. 1), it was observed that the differential cross sections for production of the second excited state were substantially smaller than those for production of the ground and first excited states, which are adequately described by the conventional shell model of the nucleus that assumes an inert O^{16} core. However, the differential cross sections are not negligible, and the angular distribution displays many of the characteristics of a direct interaction process. The direct knockout of an alpha particle from the target is a possible mechanism for these transitions. How-

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ever, the evidence is not conclusive.

Clearly, more experimental information is required. This need can be partially satisfied by an investigation of the $\text{Sc}^{45}(\text{d}, \alpha)\text{Ca}^{43}$ reaction, since the third and fourth excited states of calcium 43 are core-excited states. The results of the measurements of the differential cross sections for production of these states as well as of the ground, first, second, and fifth excited states of Ca^{43} are reported herein.

SYMBOLS

E_d	deuteron energy
Q	reaction Q-value
α_i	alpha particle, which corresponds to production of i^{th} state in residual nucleus
θ_{cm}	center-of-mass reaction angle, deg
θ_{lab}	laboratory reaction angle, deg
$d\sigma/d\Omega$	differential cross section, $\mu\text{b}/\text{sr}$
$\Delta\sigma$	statistical uncertainty in differential cross section

PROCEDURE

The experimental detection and the particle discrimination were the same as in a previous (d, α) experiment (ref. 2). The scandium 45 target was a 0.926-milligram-per-square-centimeter self-supporting foil (obtained from Oak Ridge National Laboratory).

RESULTS

The overall energy resolution was sufficient to allow the separation of six alpha-particle groups representing the ground and first five excited states of Ca^{43} . A typical alpha-particle spectrum is shown in figure 1. The alpha-particle groups indicated correlate with the states of Ca^{43} , as shown in figure 2. The experimental results are presented in table I and in figures 3 to 5. The errors shown are statistical uncertainties and, if not specified, are less than the size of the point. The probable systematic error in the absolute differential cross section is assessed to be 15 percent. For purposes of illustration, the angular distributions corresponding to the core-excited states of Ca^{43} are grouped together.

DISCUSSION

The spins and parities of the states of Ca^{43} involved in this study (fig. 2) are taken from reference 3. In the shell-model formulation, the odd-parity states of Sc^{45} and Ca^{43} are achieved by the coupling of an odd number of $1f_{7/2}$ nucleons. The ground-state spin and parity of Sc^{45} are attributed to the coupling of four $1f_{7/2}$ neutrons and one $1f_{7/2}$ proton. According to McCullen, Bayman, and Zamick (ref. 4), the dominant configuration of the five nucleons which gives rise to the observed spin and parity of $7/2^-$ is that in which the four neutrons couple to zero spin. Similarly, in Ca^{43} , two of the neutrons couple to zero spin and thus leave an unpaired neutron in a $1f_{7/2}$ shell-model state. The remaining odd-parity states of Ca^{43} require a recoupling of the three $1f_{7/2}$ neutrons for their formation. The two even-parity states require excitation of the nuclear core, which for Ca^{43} is Ca^{40} .

Although the differential cross sections are not particularly large, the ground state of Ca^{43} is clearly preferentially populated if compared with the other states studied. This enhancement indicates a relatively large degree of overlap of the ground-state configurations of Sc^{45} and Ca^{43} . This overlap is consistent with the wave functions for these states as calculated by McCullen, et al. (ref. 4) and would imply that the ground state of Ca^{43} is comparatively easily formed by the simple extraction of a neutron-proton pair from Sc^{45} .

The next five states of Ca^{43} are weakly excited. This is seen from an inspection of both the alpha-particle spectrum and the angular distributions (figs. 1, 4, and 5). All five angular distributions are peaked at forward angles and have some semblance of an oscillatory pattern, which suggests a direct interaction process. The differential cross sections for the transitions leading to the even-parity core-excited states of Ca^{43} are only slightly smaller than those leading to the odd-parity states. Transitions to these states are expected to be inhibited, since the formation of the odd-parity states requires a recoupling of the $1f_{7/2}$ neutrons in Ca^{43} , and the formation of the even-parity states requires not only recoupling of the $1f_{7/2}$ neutrons but also excitation of the nuclear core of Ca^{43} . Thus, a situation arises which is much like that in the $\text{F}^{19}(\text{d}, \alpha)\text{O}^{17}$ reaction. Transitions leading to core-excited states in the residual nucleus are indeed small but are comparable to transitions leading to the better understood shell-model states.

CONCLUDING REMARKS

The character of all six angular distributions measured is indicative of a direct interaction process. The preferential production of the ground state of Ca^{43} suggests that the reaction proceeds by picking up a neutron-proton pair from Sc^{45} . This interpretation

is consistent with the shell-model wave functions for the ground states of these two nuclei. The differential cross sections for production of the remaining five states of Ca^{43} are comparable and are, in general, more than one order of magnitude smaller than those for production of the Ca^{43} ground state. The differential cross sections for production of the core-excited states of Ca^{43} are small but not negligible. The effect is similar to that observed in the $\text{F}^{19}(\text{d}, \alpha)\text{O}^{17}$ reaction and awaits a theoretical interpretation.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 18, 1967,
129-02-04-06-22.

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1. Priest, Joseph R.; and Vincent, John S.: Interpretation of (d, α) Reactions on Fluorine 19 and Nitrogen 15. NASA TN D-3813, 1967.
2. Priest, Joseph R.; and Vincent, John S.: Investigation of the (d, α) Reaction on Aluminum 27. NASA TN D-3548, 1967.
3. Endt, P. M.; and Van der Leun, C.: Energy Levels of Light Nuclei. III. $Z = 11$ to $Z = 20$. Nucl. Phys., vol. 34, 1962, pp. 1-340.
4. McCullen, J. D.; Bayman, B. F.; and Zamick, Larry: Spectroscopy in the Nuclear $1f_{7/2}$ Shell. Phys. Rev., vol. 134, no. 3B, May 11, 1964, pp. 515-538.

TABLE I. - EXPERIMENTAL DATA FOR $\text{Sc}^{45}(\text{d}, \alpha)\text{Ca}^{43}$

(a) Ground state			(b) First excited state		
Center-of-mass reaction angle, θ_{cm} , deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr	Statistical error, $\Delta\sigma$, fm^2/sr	Center-of-mass reaction angle, θ_{cm} , deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr	Statistical error, $\Delta\sigma$, fm^2/sr
15.8	142.4×10^{-4}	8.1×10^{-4}	15.8	15.0×10^{-4}	2.6×10^{-4}
21.1	140.0	8.0	21.1	14.6	2.6
26.3	105.6	7.0	26.3	7.8	1.9
26.3	112.6	4.5	26.3	7.8	1.2
31.6	99.4	4.3	31.6	8.6	1.3
36.8	76.3	3.7	36.8	5.3	1.0
42.0	62.0	1.0	42.0	4.0	.5
47.2	48.7	.9	47.2	3.4	.5
52.4	36.8	.8	52.4	2.3	.4
42.0	64.1	2.1	57.6	3.2	.2
47.2	47.4	1.8	67.9	1.4	.1
52.4	38.0	1.6	73.0	1.5	.1
57.6	28.1	.7	78.0	1.8	.1
62.7	21.3	.4	88.1	1.5	.1
67.8	16.0	.4	98.1	1.2	.1
72.9	15.9	.4	(c) Second excited state		
78.0	14.3	.4	15.8	19.1×10^{-4}	3.0×10^{-4}
83.1	13.1	.4	21.1	10.5	2.2
88.1	12.1	.4	26.3	10.1	2.2
93.1	11.5	.4	26.3	14.2	1.6
98.1	10.1	.3	31.6	9.7	1.3
103.1	10.4	.3	36.8	6.4	1.1
108.0	9.3	.3	42.0	4.3	.5
112.9	7.8	.3	47.2	2.7	.4
117.8	6.3	.3	52.4	1.9	.4
112.6	6.0	.3	57.6	2.0	.2
132.4	5.4	.3	67.9	2.3	.1
137.2	4.9	.2	73.0	2.2	.1
146.8	4.7	.3	78.1	2.1	.1
151.6	4.6	.3	88.1	1.5	.1
156.3	4.0	.3	98.1	1.3	.1
156.3	4.4	.3			
161.1	3.9	.3			
165.8	3.8	.3			

TABLE I. - Concluded. EXPERIMENTAL DATA FOR $\text{Sc}^{45}(\text{d}, \alpha)\text{Ca}^{43}$

(d) Third excited state			(f) Fifth excited state		
Center-of-mass reaction angle, θ_{cm} , deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr	Statistical error, $\Delta\sigma$, fm^2/sr	Center-of-mass reaction angle, θ_{cm} , deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr	Statistical error, $\Delta\sigma$, fm^2/sr
15.8	14.6×10^{-4}	2.6×10^{-4}	15.8	16.8×10^{-4}	2.8×10^{-4}
21.1	7.3	1.8	21.1	14.1	2.5
26.3	10.5	2.2	26.4	13.7	2.5
26.3	9.3	1.3	26.4	10.7	1.4
31.6	7.3	1.2	31.6	10.6	1.4
36.8	4.0	.9	36.8	5.9	1.0
42.0	4.2	.5	42.1	5.2	.6
47.3	2.3	.4	47.3	6.0	.6
52.4	1.9	.4	52.5	5.4	.6
57.6	.9	.1	57.6	3.9	.3
67.9	1.2	.1	67.9	3.8	.2
73.0	.7	.1	73.0	2.7	.2
78.1	.8	.1	78.1	2.9	.2
88.2	.5	.1	98.2	2.3	.2
98.2	.5	.1			
(e) Fourth excited state					
15.8	7.3×10^{-4}	1.8×10^{-4}			
21.1	5.0	1.5			
26.4	2.3	1.0			
26.4	2.7	.7			
31.6	2.6	.7			
36.8	1.1	.5			
42.1	2.1	.4			
47.3	1.0	.3			
52.5	.9	.2			
57.6	.6	.1			
67.9	.5	.1			
73.0	.7	.1			
78.1	.5	.1			
98.2	.3	.1			

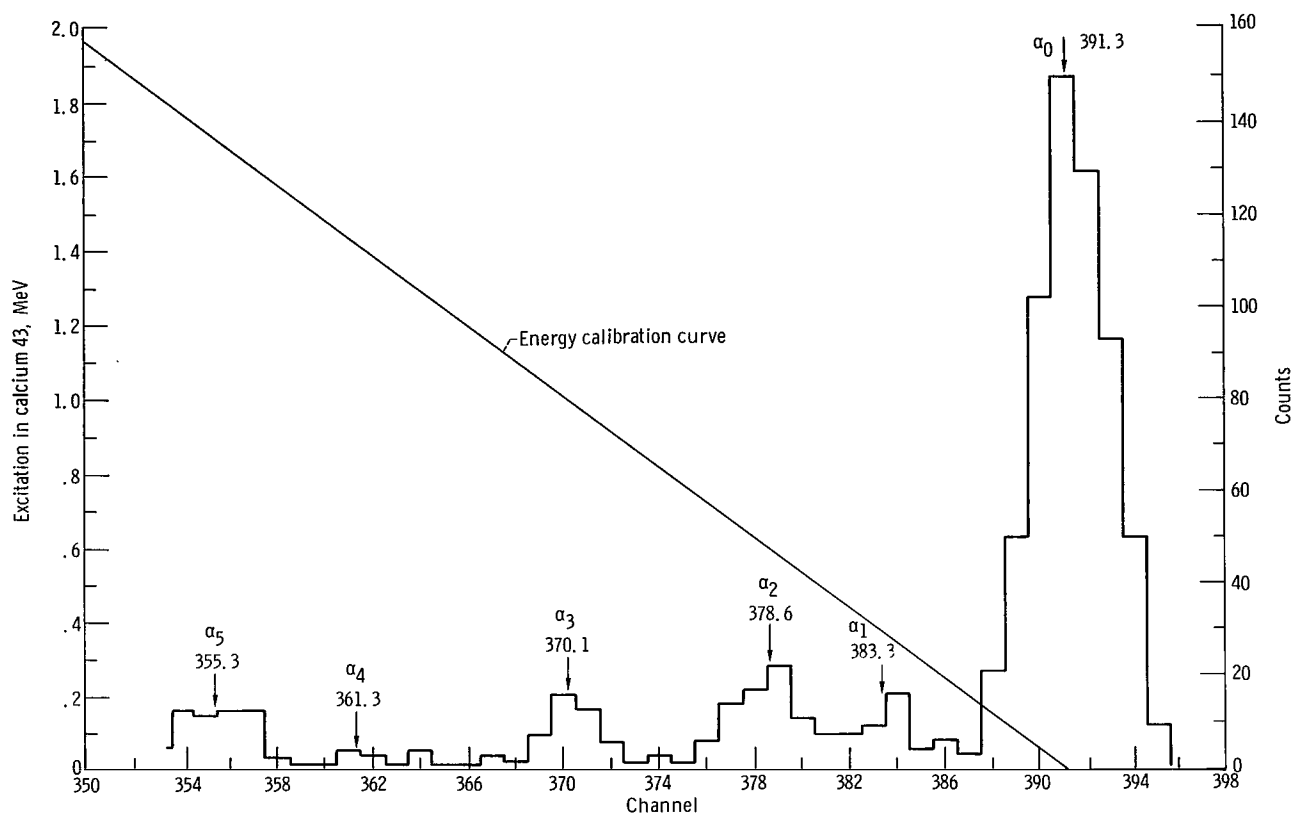


Figure 1. - Typical alpha-particle spectrum and energy calibration curve for $\text{Sc}^{45}(\text{d}, \alpha)\text{Ca}^{43}$ reaction. Laboratory reaction angle, θ_{lab} , 25° ; number and arrow on each group indicate calculated value of centroid of that group.

Excitation energy, MeV	Spin and parity (J)
1.904 (3.05×10^{-13})	
1.678 (2.69×10^{-13})	$(11/2^-)$
1.389 (2.22×10^{-13})	$3/2^+$
0.993 (1.59×10^{-13})	$5/2^+$
0.594 (0.95×10^{-13})	$3/2^-$
0.374 (0.60×10^{-13})	$5/2^-$
0 (0)	$7/2^-$

Figure 2. - Low-lying energy levels of calcium 43.

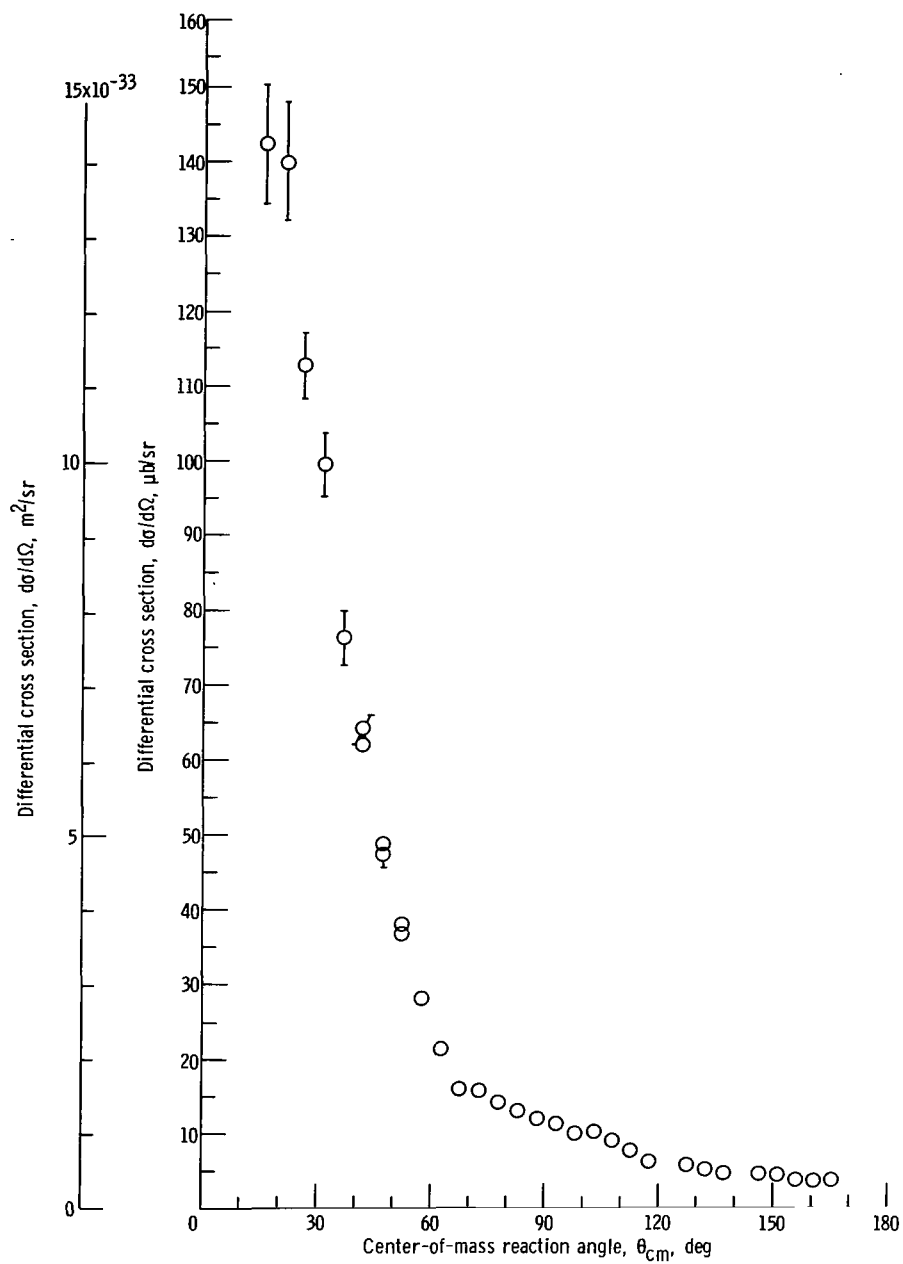
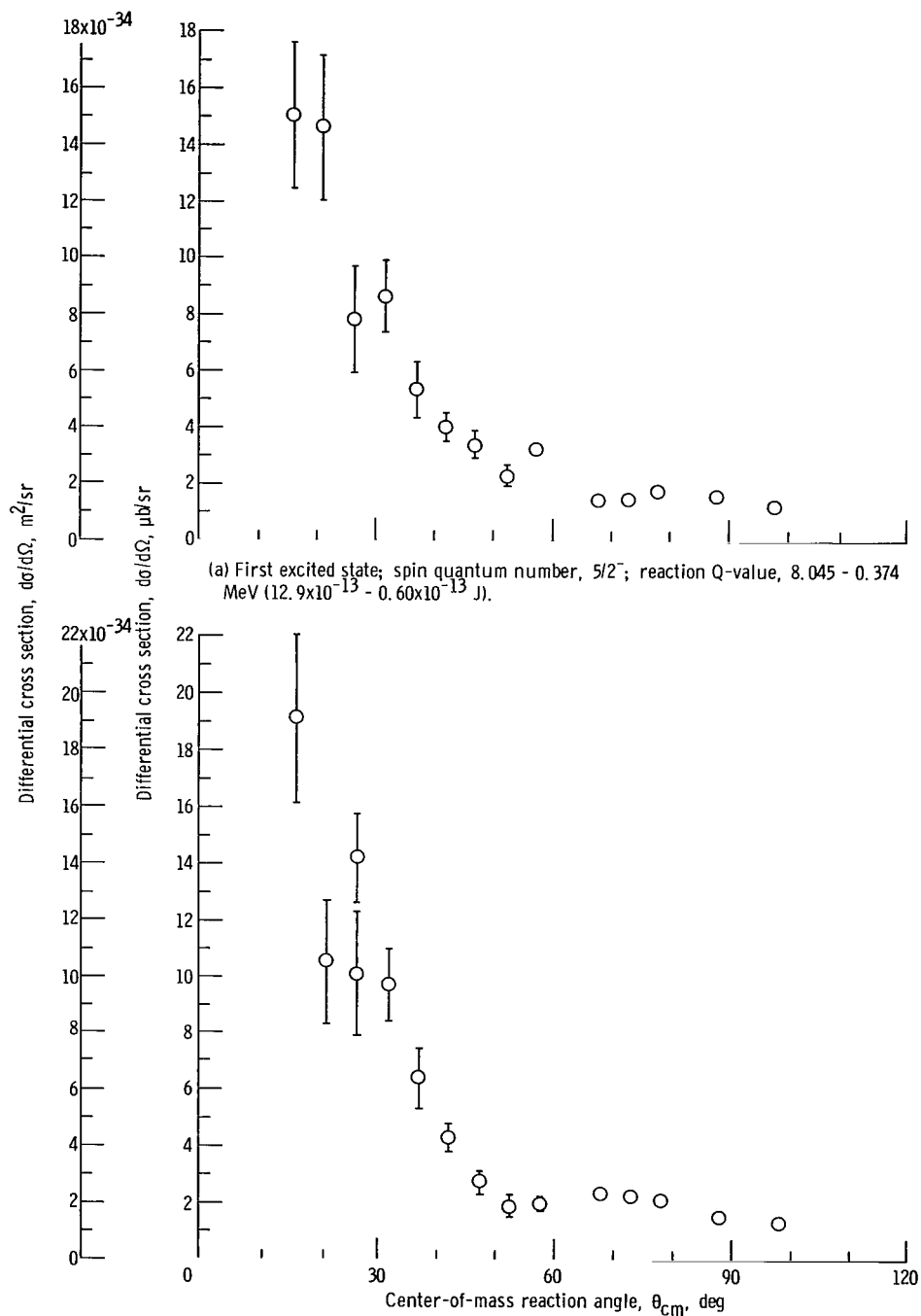


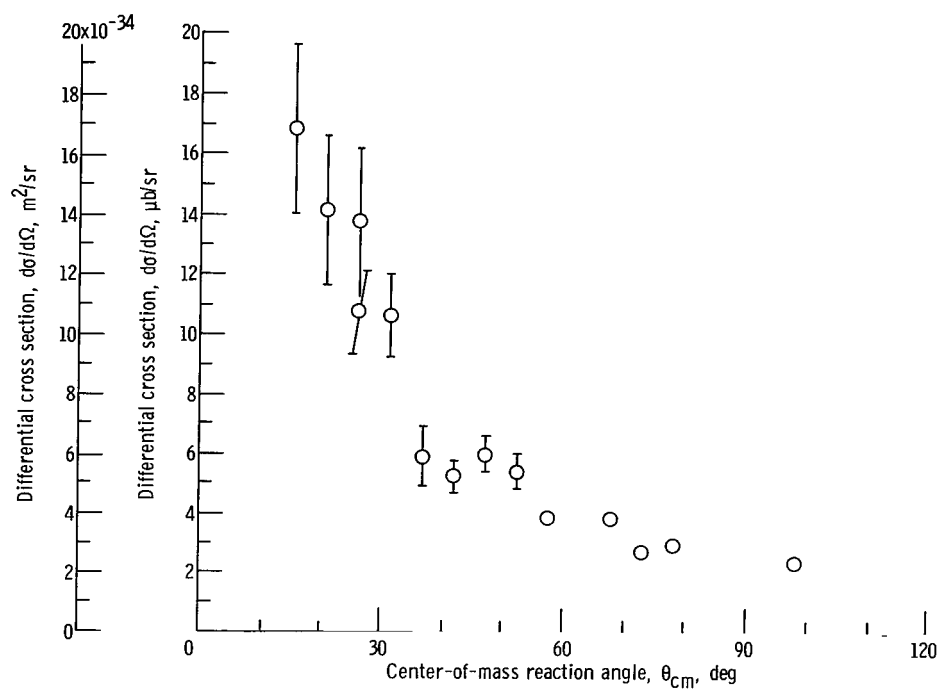
Figure 3. - Angular distribution of differential cross sections for $Sc^{45}(d,\alpha)Ca^{43}$ reaction. Ground state; spin quantum number, $7/2^-$; reaction Q-value, 8.045 MeV (12.9×10^{-13} J).



(a) First excited state; spin quantum number, $5/2^-$; reaction Q-value, $8.045 - 0.374$ MeV ($12.9 \times 10^{-13} - 0.60 \times 10^{-13}$ J).

(b) Second excited state; spin quantum number, $3/2^-$; reaction Q-value, $8.045 - 0.594$ MeV ($12.9 \times 10^{-13} - 0.95 \times 10^{-13}$ J).

Figure 4. - Angular distributions of differential cross sections for $\text{Sc}^{45}(\text{d}, \alpha)\text{Ca}^{43}$ reaction leaving calcium 43 in its odd-parity states.



(c) Fifth excited state; spin quantum number, $11/2^-$; reaction Q-value, $8.045 - 1.678$ MeV ($12.9 \times 10^{-13} - 2.69 \times 10^{-13}$ J).

Figure 4. - Concluded.

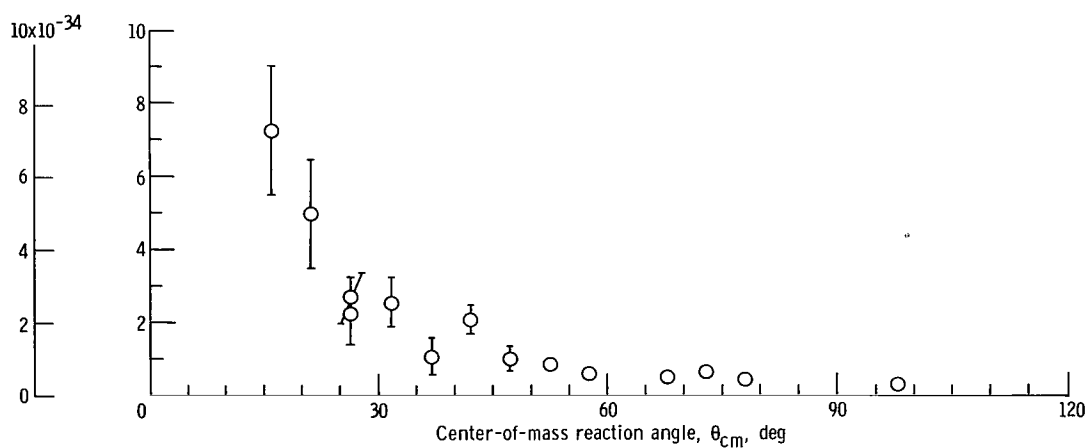
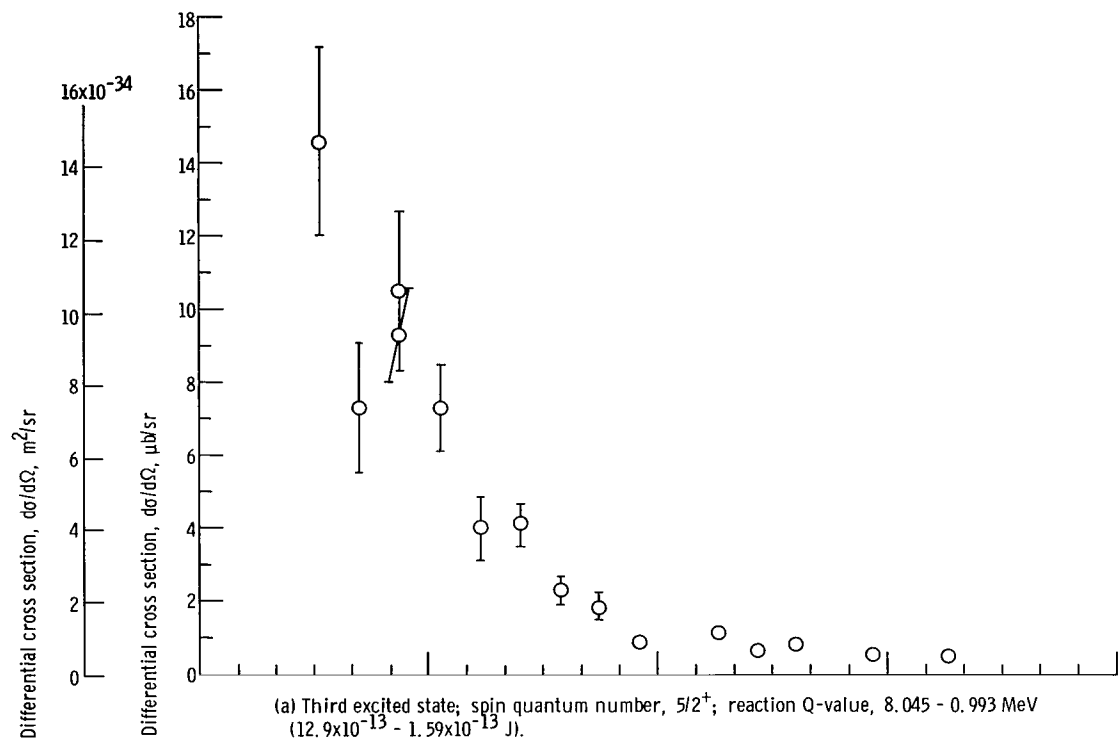


Figure 5. - Angular distributions of differential cross sections for $\text{Sc}^{45}(\text{d}, \alpha)\text{Ca}^{43}$ reaction, leaving calcium 43 in its even-parity states.

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